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TO WHAT DEGREE THERMAL CYCLES AFFECT CHALK STRENGTH

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ABSTRACT

Chalk reservoirs could potentially undergo destabilization as the result of repeated cold water injection into a hot reservoir during water flooding. Preliminary results of an ongoing study are presented in this paper, which compare the impact of temperature cycling on mechanical behavior on dry and water saturated chalk. Sixty disks of dry Kansas chalk exposed to different number of temperature cycles were tested for tensile strength using a Brazilian test. Changes in elastic properties as function of number of temperature cycles of the same chalk, but now saturated in water, were studied using triaxial cell experiments. For dry rock, no significant effects of temperature cycling was found on average tensile strength, however the range of the tensile failure stress is doubled for the samples exposed to 50 temperature cycles, as opposed to those to none. For water saturated cores, the temperature cycling had a significant effect and a significant accumulative irreversible deformation was seen for the core exposed to cyclical temperature variations, so that the elastic bulk modulus consequently increased more than for a core that had been tested at constant temperature. The inconsistency of the results from the two tests suggests the importance of the pore fluid.

INTRODUCTION

Thermal cycling effects are observed on (calcitic) marble cladding, which after being exposed to repeated seasonal change, experience considerable deformation. A famous example is the degradation of marble cladding on the Finlandia Hall in Helsinki [1]. Similar to marble, chalk is mostly composed of calcite. The thermal expansion of calcite is temperature dependent, and very anisotropic [2], so when temperature is increased the grain expands parallel to the c-axis, but also contracts in the perpendicular direction. The deformation observed in marble probably arises due to the combined effect of the expansion of single calcite crystals, the difference in the thermal expansion coefficient and the angle between neighboring crystals. Decoupling of reversible and irreversible processes is another important factor to consider when rock is exposed to stress. The total strain is defined as the sum of the irreversible ε_{irr} and reversible ε_{rev} strain,

$$\varepsilon_{tot} = \varepsilon_{irr} + \varepsilon_{rev}. \tag{1}$$

As plastic deformation accumulates the rock becomes stiffer and harder to further deform, such that the rock is hardened by plastic deformation. This phenomenon is called work hardening.

PROCEDURE

Material

Chalk is a carbonate rock mostly composed of calcitic coccoliths originating from skeletons of algae. The grains in chalk are held together by contact cement and attractive van der Waals forces at short distances between the particles, counteracted by electrostatic repulsion at intermediate distance. These forces are dependent on temperature and brine composition [3-5].

Chalk from Kansas (USA) was used in this study. It is an indurated chalk with wackestone texture. Petrophysical properties of selected samples are listed in Table 1. The average porosity ϕ was calculated to be 34%, permeability was measured to be 0.3 and 0.9 mD, and elastic wave velocity, V_p, around 3000 m/s. The samples thus resemble North Sea reservoir chalk with respect to porosity, permeability, and induration.

Table 1. Petrophysical properties of selected samples for the Brazilian test.

Sample number	# of cycles	ϕ-sat. (%)	Diameter (mm)	Length (mm)	V_p (m/s)	He-gas (g/cm^3)	ϕ-He gas (%)
K1-3	0	35.1	38.09	26.28	2857	2.71	35.7
K1-4	30	33.9	38.10	27.51	3057	2.72	34.9
K2-1	50	34.7	38.09	26.95	2929	2.70	34.7
K2-5	15	30.9	38.09	23.21	3179	2.70	31.2
K4-2	0	34.9	38.10	26.04	2504	2.69	35.0
K5-3	30	34.6	38.10	22.83	2890	2.69	34.6
K6-3	15	33.8	38.08	30.09	2812	2.71	34.4
K7-1	8	34.8	38.08	25.26	2476	2.71	36.0
K8-5	8	32.6	38.10	19.59	3160	2.69	32.5
K10-6	50	33.4	38.13	22.63	2487	2.69	34.4

Brazilian test

Precautions were taken to keep track of the spatial directions in the block to remove any anisotropy effects that would affect direct comparison._Long cores were shaped and cut into disks with diameters double the length. 60 samples were prepared. After drying at 120ºC overnight, each sample was weighed and saturated in a vacuum chamber with distilled water to estimate porosity and solid density. He-gas pycnometry was used to confirm measures of the solid density and porosity. The dried samples were then repeatedly heated and cooled and the effect on the tensile strength in Brazilian tests were investigated. Dry samples were used to single out the effects of temperature fluctuations, without the influence that pore fluids might have.

In Brazilian tests, the tensile strength (T_0) at failure is estimated from the critical force (F) applied by two parallel plates, $T_0 = 2F/\pi DL$, where D and L are diameter and length of the sample. 10 samples were tested directly before any temperature cycling was performed. The other 50 specimens were put in an oven at 135°C for 8h, and then switched off for 16h, allowing the samples to cool. After eight temperature cycles 10 samples were tested, and the rest of the samples were tested after 15, 30 and 50 cycles (see Table 2).

Hydrostatic test

Two cores from the same chalk block were prepared for testing in a triaxial cell, and saturated with calcite equilibrated brine that was prepared by placing chalk pieces in distilled water. The average pH of the brines were 8.7 and the salinity were approx. 300 ppm (ion chromatography). The triaxial cell has two pumps to control the confining pressure (P_c) and fluid pressure (P_f). The cell is additionally equipped with a heating jacket which allows temperature control, as well as with extensimeter and internal LVDT to measure radial and axial deformation of the core. The elastic bulk modulus (K_b) is measured using Equation 3. For both cores, the modulus is calculated for both the loading phase and unloading phase.

$$K_b = \frac{P_c}{\varepsilon_{vol}}\ , \qquad (2)$$

Each core was mounted into the triaxial cell, followed by increasing the P_c to 0.5 MPa. Next, P_f and P_c were increased to 0.7 and 1.2 MPa respectively. Then each core was tested: one was subjected to confining pressure cycling alone, where the temperature was kept constant at 30ºC throughout the test. The second experiment included a temperature cycle for each stress cycle that could be compared to the constant temperature experiment. Each morning, at 30ºC, a confining stress cycle was performed to measure stress-strain behavior and to quantify the elastic bulk modulus. The stress cycle is characterized by a loading phase (1.2→5.2 MPa) and unloading (5.2→1.2 MPa), 30 minutes each way. The bulk modulus was measured as an average during both loading and unloading phase of each cycle, along with the reversible and irreversible strain components. Directly after each stress cycle, the cell-temperature was increased to 130ºC, and six hours later the temperature was reduced back to 30ºC. This procedure was repeated daily to explore the evolution in the strain and bulk modulus for 10 days. An additional 11th cycle was performed on the core, however this cycle did not include the temperature variation. This was done in order to confirm if the effects observed were temperature and not sample dependent.

RESULTS

The results of the Brazilian tests for tensile strength T_0 and the dynamic evolution of the stress-strain behavior during hydrostatic loading are shown here.

Brazilian Test

Average tensile strength for each temperature cycling procedure is presented in Table 2. The average tensile strength does not show any significant response to temperature cycling, however the distribution of the data is significantly broader when the samples have been exposed to temperature cycling. The standard deviation is doubled for samples

Table 2. Average tensile strength failure for the Brazilian tests and their std. dev.

# of cycles	# of tests	T_0 (MPa)	Std. dev (MPa)
0	10	3.10	0.40
8	10	3.07	0.62
15	15	3.30	0.50
30	10	3.32	0.58
50	15	3.08	0.82

exposed to 50 temperature cycles as opposed to those unaged. Figure 1 (a) illustrates the distribution of tensile strengths at which chalk fails. Figure 1 (b) shows that there is no obvious trend between porosity and the failure strength, indicating that the results obtained are not porosity dependent.

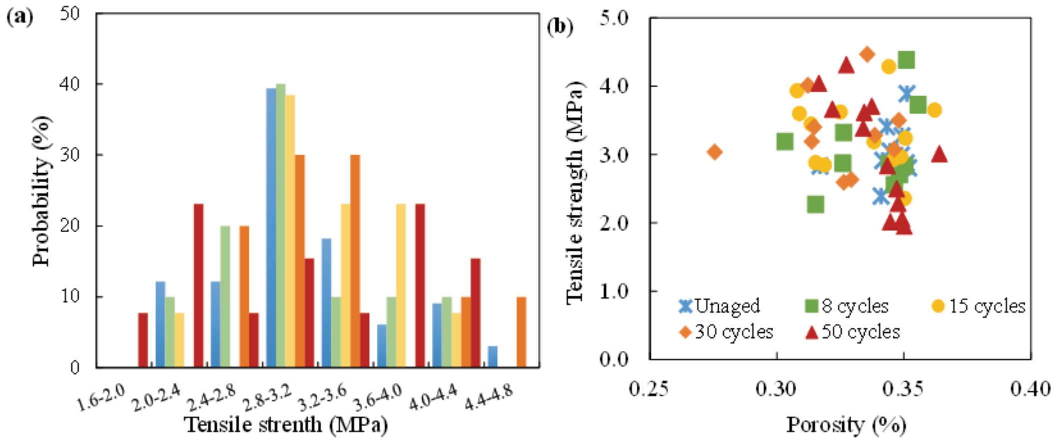

Figure 1. Results from the Brazilian test: (a) probability of the sample to fail within a tensile strength range; (c) Tensile strength shows no dependency on porosity.

Hydrostatic test

The results of the two experiments are presented in Table 3 and Figure 2 (for all values in the figures, but every second in the table). The irreversible fraction of the total strain during each stress cycle $\varepsilon_{irr}/\varepsilon_{tot}$ was calculated by modifying Equation 1, and is shown in Table 3. To ensure the comparability of the results, the first cycle for both experiments was completed without any temperature variation. K_b and the strain fraction for both experiments during loading and unloading phase have similar values. But once the temperature cycling was applied to one of the cores, the fraction is much higher for cycles in the experiment where temperature is varied (Figure 3). The additional 11th cycle proves this effect does not depend on the strain but on the temperature cycling. The K_b of the core with constant temperature increases slightly during loading and decreases slightly during unloading. However, for the core treated with heating/cooling cycles, K_b increases more significantly during loading and unloading as irreversible strain increase.

Table 3. K_b and irreversible fraction of strain (*additional cycle with const. temp.)

# of cycles	**Constant temperature**			**Temperature cycling**		
	K_b load (GPa)	K_b unload (GPa)	$\varepsilon_{irr} / \varepsilon_{tot}$ (%)	K_b load (GPa)	K_b unload (GPa)	$\varepsilon_{irr} / \varepsilon_{tot}$ (%)
1	1.60	3.07	48.2	1.64	2.91	44.1
2	2.44	2.77	14.7	2.26	2.95	28.3
4	2.48	2.71	7.2	2.67	3.40	21.6
6	2.47	2.64	7.0	2.74	3.37	18.0
8	2.50	2.66	5.5	2.79	3.28	17.5
10	2.52	2.55	4.0	2.79	3.58	17.8
11	/	/	/	3.23*	3.43*	2.55*

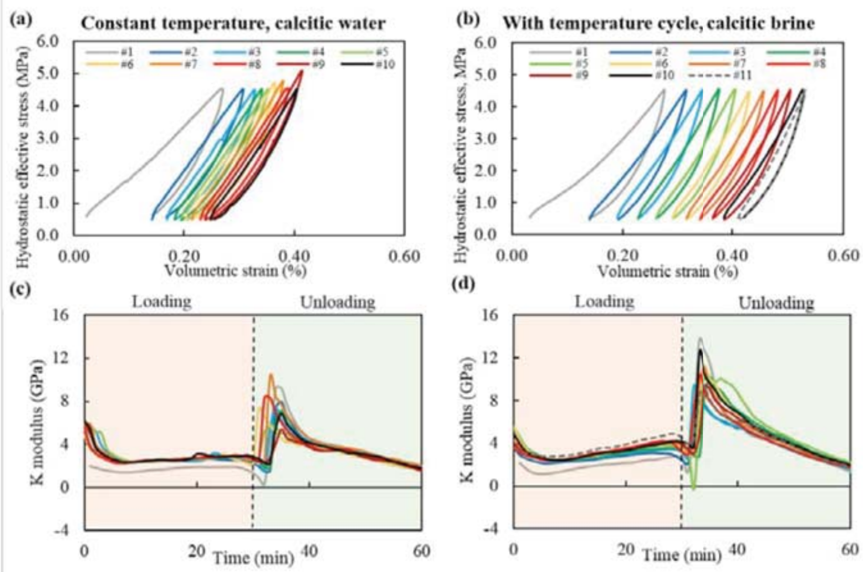

Figure 2. Hydrostatic test results for constant temperature in the left column (a and c) and with temperature cycling in the right column (b and d). Stress versus volume strain in (a) and (b). Slopes during loading and unloading in (c) and (d).

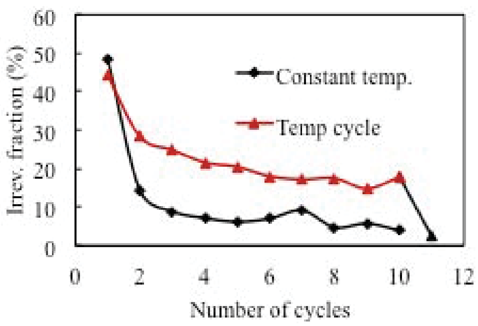

Figure 3. Irreversible strain fraction, $\varepsilon_{irr}/\varepsilon_{tot}$, for individual hydrostatic cycles.

DISCUSSION

Brazilian tensile failure of dry chalk displays no weakening of tensile strength for increasing numbers of temperature cycles, except an increased spread in the tensile strength after 50 cycles (Table 2). For the saturated cores in the hydrostatic tests, the fraction of irreversible strain, $\varepsilon_{irr}/\varepsilon_{tot}$, is significantly higher when temperature has been cycled between each stress cycle (Figure 3). After 10 stress cycles the temperature exposed core accumulates 0.40% total volumetric strain as opposed to the constant temperature core that only accumulated 0.25% (Figure 2 a and b). In fact, the core exposed to the temperature cycling reaches 0.25% irreversible deformation after only 4 cycles. The 11th cycle that was performed with constant temperature, shows that the irreversible fraction drops down to 2.5%, which is comparable to the constant temperature experiment (Figure 3). This shows that the magnitude of the irreversible component is due to the temperature cycling. The evolution of the elastic stiffness during loading and unloading (K_b) with respect to number of cycles is different between the constant temperature and temperature cycle tests (Table 3). K_b during unloading is reduced for the constant temperature while increases for the temperature exposed cores, while K_b during loading increases independent of temperature exposure. In reservoirs, the accumulation of irreversible deformation alters the pore volume and thus the reservoir permeability. Variations in temperature and effective stresses are expected since injection rates may vary, thus impacting the irreversible strain component. The results from the Brazilian tests and hydrostatic test seem not to show a clear relation between temperature variations and mechanical strength. This may indicate the importance of either the pore fluid, or inconsistencies of mechanical properties tested (tensile vs compaction).

CONCLUSION

Two different tests procedures were performed on Kansas chalk to determine if temperature cycling has an effect on chalk mechanical strength. The Brazilian test on dry samples reveals no significant weakening observed with temperature cycling. Hydrostatic tests show that temperature cycling on water saturated samples has an effect on the reversible and irreversible strain partitioning, and the bulk modulus during loading and unloading. At this point, presented evidence does not univocally show if thermal expansion coefficients play a role in dictating the mechanical strength of chalk.

NOMENCLATURE

ϕ	Porosity	L	Length	K_b	El. bulk modulus
V_p	P wave velocity	D	Diameter	ε_{vol}	Vol. strain
F	Force	P_c	Confining pres.	ε_{irr}	Irr. strain comp.
T_o	Tensile strength	P_f	Pore fluid pressure	ε_{tot}	Total strain

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